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Potential production of bioenergy from biomass in an Indian perspective

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ABSTRACT

Concerns over climate change, fossil fuel depletion, and increase in natural gas prices have sparked a great interest in various forms of renewable energy and its imposition, particularly in developing countries. Biomass is utilized as number one energy resource for developing countries, supplying energy to households for cooking purposes, and signifying about 70–80% of the global bioenergy contributions. India has vast biomass resources and wasteland to support cultivation of bioenergy crops, the potential of that can be harnessed to resolve energy crisis. Bioenergy can contribute to energy security whilst also decreasing the emissions of greenhouse gases from fossil fuels. The objective of this review is to give an overview of biomass energy potential and its utilization in India, state of the art of the technologies used for biomass conversion, and latest development in biomass conversion technologies.

Contents

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Conversion factors commonly used in bioenergy production

Energy units
Quantities

- 1.0 joule (J) = one Newton applied over a distance of one meter (= 1 kg m^2/s^2)
- 1.0 J = 0.239 calories (cal)
- 1.0 cal = 4.187 J
- 1.0 gigajoule (GJ) = 10^9 J = 0.948 million Btu = 239 million cal = 278 kWh
- 1.0 British thermal unit (Btu) = 1055 J (1.055 kJ)
- 1.0 Quad = One quadrillion Btu (10^{15} Btu) = 1.055 exajoules (EJ), or approximately 172 million barrels of oil equivalent (boe)
- 1000 Btu/lb = 2.33 gigajoules per ton (GJ/t)
- 1000 Btu/US gallon = 0.279 megajoules per liter (MJ/l)

Energy costs
$1.00 per million Btu = $0.948/GJ
$1.00/GJ = $1.055 per million Btu

Fossil fuels

- Barrel of oil equivalent (boe) = approx. 6.1 GJ (5.8 million Btu), equivalent to
- 1700 kWh. "Petroleum barrel" is a liquid measure equal to 42 U.S. gallons (35 Imperial gallons or 159 l); about 7.2 barrels oil are equivalent to 1 ton of oil (metric) = 42–45 GJ.
- Gasoline: US gallon = 115,000 Btu = 121 MJ = 32 MJ/l (LHV). HHV = 125,000 Btu/gal = 132 MJ/gal = 35 MJ/l
- Metric ton gasoline = 8.53 barrels = 1356 l = 43.5 GJ/t (LHV); 47.3 GJ/t (HHV)
- Gasoline density (average) = 0.73 g/ml (= metric ton/m^3)
- Petro-diesel = 130,500 Btu/gal (36.4 MJ/l or 42.8 GJ/t)
- Petro-diesel density (average) = 0.84 g/ml (= metric ton/m^3)

Carbon content of fossil fuels and bioenergy feedstocks

- Coal (average) = 25.4 metric ton carbon per terajoule (TJ)
- Metric ton coal = 746 kg carbon
- Oil (average) = 19.9 metric ton carbon/TJ
- US gallon gasoline (0.833 Imperial gallon, 3.79 l) = 2.42 kg carbon
- US gallon diesel/fuel oil (0.833 Imperial gallon, 3.79 l) = 2.77 kg carbon
- Natural gas (methane) = 14.4 metric ton carbon/TJ
- Cubic meter natural gas (methane) = 0.49 kg carbon
- Carbon content of bioenergy feedstocks: approx. 50% for woody crops or wood waste; approx. 45% for graminaceous (grass) crops or agricultural residues

1. Introduction

Power plays a great role wherever man lives. Energy is a key factor for the development and social prosperity of any country. Modern society demand for energy is continuously increasing and now becomes a prime concern [1–4]. Due to industrial growth and extensive use of electrical gadgets, electricity consumption is increasing day by day. Energy is the most important issue of the 21st century. Unfortunately, the world energy demands are mainly met by the fossil fuels.

In India, the energy consumption, by world standards, is very low. Global energy average is nearly 1800 kilogram oil equivalent (kgoe) whereas per capita consumption in India is 500 kgoe. It has been assessed that 70% of petroleum requirements of India is through imports, which are expected to increase in near future. Approximately, India shares only 0.4% of the world's reserves of crude oil. According to the report published by World Energy Outlook, 94% of India's crude oil demand would be met by imports by 2030 [5]. Moreover, our demand for energy is expected to grow at an annual rate of 4.8% over the next couple of decades. Worldwide consumption of petroleum and other liquid fuels was 87 million barrels/day in 2010 and it is expected to increase to 97 million barrels/day in 2020 and 115 million barrels/day in 2040 [6] (Fig. 1). On the other hand, domestic production of crude oil from fossil fuels meets only 30 percent of the national requirement and balance is met through imports of nearly 146 million ton of crude petroleum products that cost the country close to US$90 billion in 2008–09 (Fig. 2). The projected use of fuels in India is given in Table 1.

The progressive decline of fossil fuels reserves (particularly liquid fuels and coal), and their associated harmful effects such as pollution, threatens human health and environment (greenhouse gases associated with global warming) has increased pressure to develop alternative energy program. However, in the present context petroleum serves as a preferred fuel. The increased demand for energy, energy security, and growing environmental concerns has driven the research interest for researchers to think seriously for other alternative sources of energy.

In India, use of biomass for energy production dominates particularly in rural areas (over 80%). Thus, biomass energy is a right option in this regard, because of its renewable, abundant, and environment friendly nature. Recently awareness about the use of bioenergy has been increased considerably. At present, biomass provides fuel for production of 1% of the global electricity generation. About 14% of the world, primary energy supply is provided by biomass resources which is comparable to 72 EJ/year, and 38% of total energy supply in case of developing countries [6]. Most of the biomass is consumed in rural areas of developing countries. Estimation suggests that from biomass India derives about 47%, Kenya 68%, Pakistan 27%, Brazil 25%, and China 13% of their total energy. Beringer et al. [7] calculated the global bioenergy potentials of biomass sources under environmental and agricultural constraints and concluded that bioenergy may provide about 130–270 EJ/year in 2050, equivalent to 15–25% of the world's future energy demands.

Except US, Brazil and some European countries, production of modern bioenergy and more specifically liquid biofuels around the world is still limited and it is in the developing stage in developing countries [8]. In African continent the potential for conversion of biomass to bioenergy exists but not really started because of lack of capacity, infrastructure, investment and food security concerns.

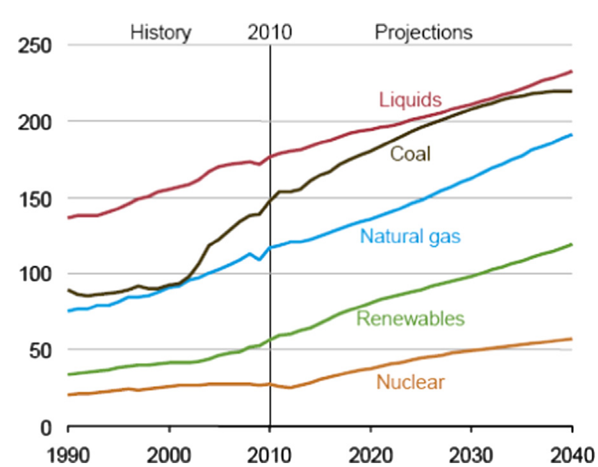


Fig. 1. World energy consumption by fuel type, 1990–2040 (Quadrillion Btu).

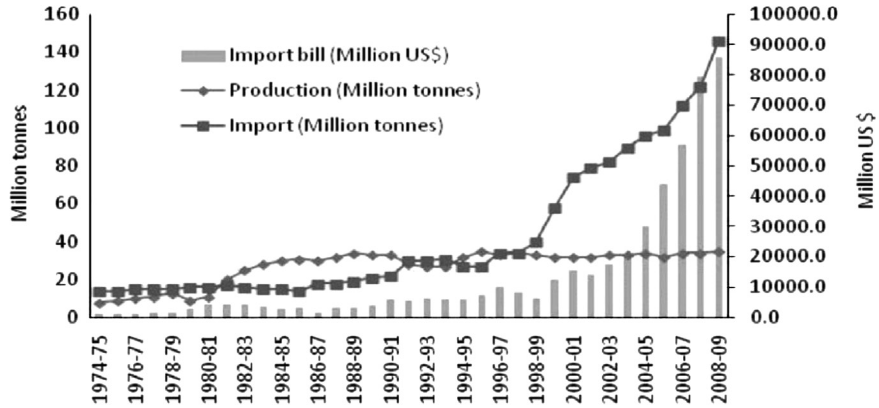


Fig. 2. Domestic production and import of crude oil in India: 1974–75 to 2008–09 [22].

Table 1
Projected use of fuel in India (Billion Liters).
Source: GAIN Report 2013. [73].

Calendar year	2015	2016	2017	2018	2019	2020	2021	2022	2023
Gasoline total	28	30	32	35	37	40	43	47	50
Diesel total	94	97	101	106	110	115	119	124	129
On-road	56	58	61	63	66	69	72	74	78
Agriculture	11	12	12	13	13	14	14	15	16
Construction/ mining	4	4	4	4	4	5	5	5	5
Shipping/rail	5	5	5	5	5	6	6	6	6
Industry	10	11	11	12	12	13	13	14	14
*Heating	7	8	8	8	9	9	10	10	10
Jet fuel total	8	9	10	10	11	12	13	14	15
Total fuel market	130	136	143	151	159	167	176	185	195

* Heating/power generation proportion of diesel consumption through 2023 are indicative only.

A large number of investors have ventured into Africa looking for opportunities for natural resource exploitation particularly biofuel crops. Very few countries in the African region have been able to establish a clear policy to guide bioenergy investment. Governments of Asian countries are promoting different biofuel programs to address energy security and environmental problems. China (the 3rd largest ethanol producer in the world) and Indonesia are the largest countries in the region for bioethanol and biodiesel production. Biomass is the major source of energy in most of the developing countries [9]. Biomass for bioenergy production comes either directly from the land (dedicated energy crops), or wood coming from plantation of forests, agricultural and forest residues, and organic waste streams from various industries, food production, livestock, and by general human activities. Biomass has the largest potential in meeting the demand of future energy/fuel supply and can play a vital role in reducing greenhouse gas emissions [10,11]. Status of bioenergy development in developing countries has been reviewed by Maltsoglou et al. [8].

India stands fifth as the world's largest primary energy consumer and fourth as the largest petroleum consumer after United States, China and Japan [12]. In India, about 32% of the total primary energy comes from biomass and more than 70% of the population depend upon this energy [5]. Ministry of New and Renewable Energy (MNRE) has understood the prospective and role of bioenergy in the Indian context and initiated a nationwide effort to popularize the use of bioenergy and promote the development of efficient technologies for its practice in various sectors of the economy to ensure derivation of maximum benefits [13]. Over Rs. 600 crore per year is being invested by India for power generation from biomass and generates more than 5000 million units of electricity and mass employment yearly in the rural areas. Regarding efficient utilization of biomass, MNRE promoted bagasse-based cogeneration in sugar mills and biomass power generation under biomass power and cogeneration program. The biomass availability in India is estimated at about 500 million ton annually that comprises of residues from agriculture, agricultural industries, and forest products. MNRE indicated that 15–20% of total crop residues could be used for power generation. This implies availability of 120–150 million ton of surplus agro-industrial and agricultural residues annually that could be used for power generation. Agricultural residues and plantations by the end of the 12th Five-Year Plan can be used for harnessing 1525 MW of power [12]. In this article, attempts have been made to highlight the importance of bioenergy obtained from biomass with special reference to India. Technological developments, benefits, and future prospects of bioenergy have been discussed.

2. Biomass

In India, about 68.35 million ha are of land is lying as wasteland and this area is continuously increasing due to population pressure and overuse of fertilizers. Hence, there is a growing concern to utilize this wasteland for growing such biomass that needs less input and can be used for biofuel production [14]. Biomass is an organic matter and probably our oldest source of energy after the sun. Wood, crop, seaweed, animal wastes, etc. are composed of organic matters and are examples of biomass, which contain stored energy from the sun through a process of photosynthesis. Biomass is a renewable energy source because its supply is limitless. We can always grow trees and crops, and waste will always exist. Biomass provides a clean, renewable energy source that could dramatically improve our environment, economy and energy security. Biomass is the primary source of energy for nearly 50% of the world's population and wood biomass is a major renewable energy source in the developing world, representing a significant proportion of the rural energy supply [15].

There are primary, secondary, and tertiary resources for biomass. Primary resources include those that are produced directly by the photosynthetic process and are taken directly from the land e.g. perennial short-rotation woody crops and herbaceous crops, oil seeds and agricultural and forestry residues (e.g., wheat straw, corn stover, and the tops, limbs, and bark from trees). There are secondary and tertiary biomass resources. Physical, chemical, or biological processing of primary biomass resources gives secondary biomass resources. Tertiary biomass resources are post-consumer remainder streams e.g. animal fats and greases, used vegetable oils, packaging wastes, and construction and demolition debris.

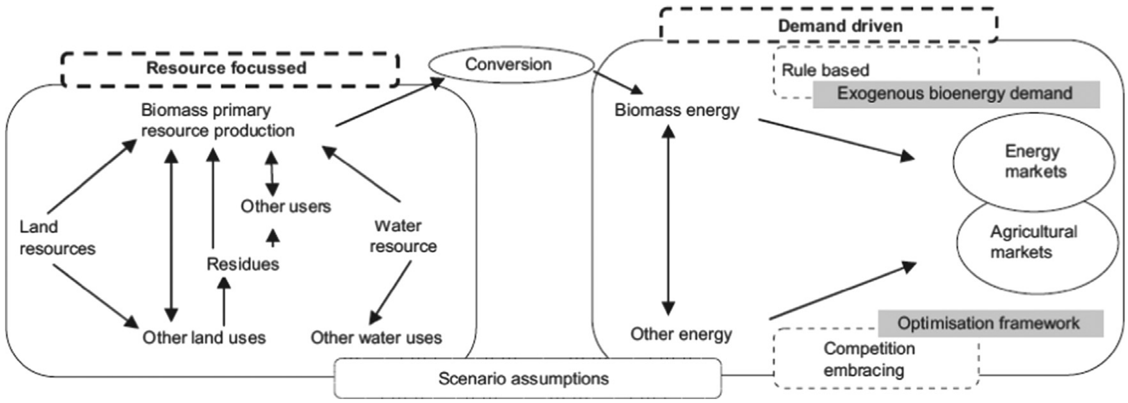


Fig. 3. Representation of resource focused and demand driven approaches [84].

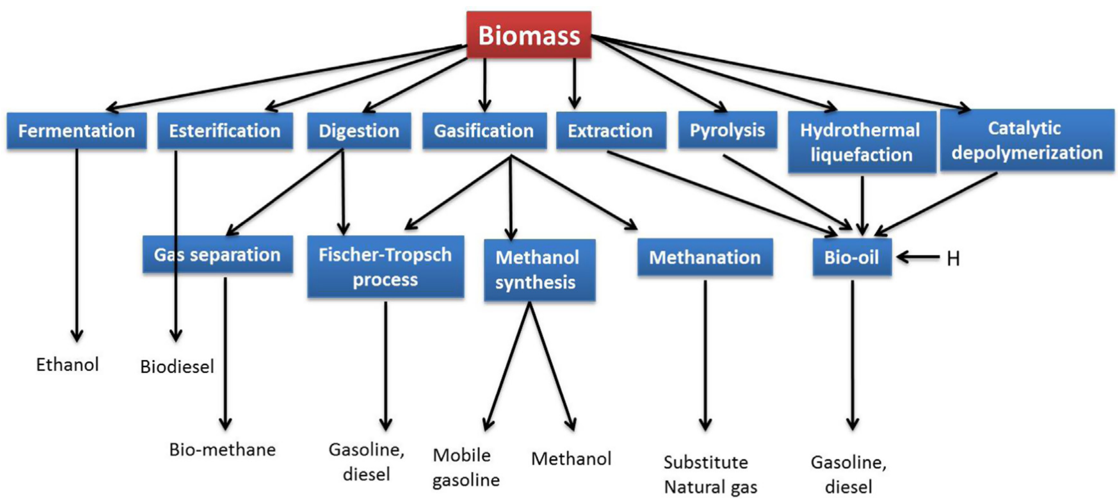


Fig. 4. Different types of fuels obtainable from biomass.

In rural India most of the population gets energy for cooking and other purposes from biomass obtained from crop residue, animal wastes, fuel wood and cow dung, etc. In addition, India has huge potential for first generation biofuels that are produced from biomass consisting of vegetable oils, animal fats, and biodegradable wastes from agriculture and industry using conventional technologies. Biomass wastes are abundant in developing countries like India and these wastes can be converted into energy using thermochemical as well as biochemical routes.

2.1. Biomass and biofuel

Most of the biomass energy assessments can be categorized as demand-driven or resource-focused assessments (Fig. 3). The abundant biomass can be used to produce various types of fuels by using different technologies (Fig. 4). Several types of biomass feedstock's can be utilized for the production of biofuels. These include agricultural lignocellulosic residues, non-edible and edible crops, and waste streams. Biochemical composition of biomass comprises of variable amounts of cellulose, hemicellulose, lignin and small amounts of other organics besides inorganics [16]. The composition and proportions of these compounds differ from plant to plant [17,18]. In plants, cell wall is made up of cellulose, composed of hydrogen bonded chains of β-1,4-linked glucose and it is coated with hemicellulose. Xylan, the most abundant type of hemicellulose, is a polymer of β-1,4-linked xylose which may have branches containing other sugars such as arabinose or glucuronic acid, depending on the plant species. The saccharification of cellulose and hemicellulose releases glucose and xylose that can in turn be fermented to ethanol. Lignin, a complex polymer of hydroxylated and methoxylated phenylpropanoids, cross-links plant secondary cell walls to provide mechanical strength and hydrophobicity and it contributes to defense against pathogens. The percentage of lignin content in cell wall varies between plants and is a crucial parameter affecting the decomposition efficiency of the polysaccharides [19]. As of now only a small amount of lignocellulosic materials, which is generated as by-products in agriculture or forestry, is used, the rest goes to waste. Lignocellulosic biomass obtained from different sources can be utilized or bioconverted into bioethanol and considered as sustainable resource for renewable fuel but commercialization of this is largely limited due to the lack of cost effective processing technologies and cost of catalyst [20]. However, relative proportion of the major organic components available in biomass is important for producing other fuels and chemicals.

3. Biomass energy potential and its utilization as energy in the India

India is the ninth largest economy in the world with 1.2 billion people and with its economic growth, there is an enormous demand for energy (expected 95%) by 2030. It has unlimited potential to hasten the use of its endowed renewable resources to power its growing economy with a secure and affordable energy supply. India has vast untapped renewable energy resources and

receives enough solar irradiation to provide many opportunities for significant annual production of biomass [21]. There is significant potential for generation of renewable energy from various sources – winds, solar, biomass, small hydro, and cogeneration bagasse [22]. The total estimated potential of renewable power generation in the country is about 89,774 MW as on 31st March 2013. This potential includes small hydropower potential of 15,399 MW (17.15%), wind power 49,130 (54.73%) and biomass power potential of 17,538 MW (19.54%) and 5000 MW (5.57%) from bagasse based cogeneration in sugar mills. Projection by 12th plan document of Planning Commission of India, indicates that total domestic energy production of 669.6 million ton of oil equivalent will be reached by 2016–17 and 844 by 2021–22 [23]. This increased energy production will meet 69% demands of expected energy consumption.

MNRE sponsored study has indicated an estimated biomass availability of about 120–150 million metric tons/annum (agricultural and forestry residues) equivalent to a potential of about 18,000 MW. Additional 5000 MW power could be generated through bagasse-based cogeneration from 550 sugar mills in the country. To support its growing population, India needs to generate two to three fold more energy than the present to sustain 8% average annual economic growth [24]. This means we need an increase in energy supply from 542 million tons of oil equivalent in 2006 to 1516 million tons of oil equivalents in 2031–2032 [25,26]. Presently India's target to play a leadership role in the emergent global green economy is driving more investment in the development of renewable energy technologies. According to Ministry report, grid-interactive renewable power capacity in the country reached 23,130 MW on 31 January 2012, which is about 11.5 percent of the total grid installed capacity in the country and contributed to about 4.5 percent to electricity generation. By the end of the Eleventh Plan period i.e. 31 March 2012, renewable power installed capacity was expected to reach over 24,000 MW. It may also be seen that due to Jawaharlal Nehru National Solar Mission, the growth of solar power is exponentially high during the Eleventh Plan period [27]. The Government of India has enacted several policies to support the expansion of renewable energy, such as Electricity Act 2003, National Electricity Policy 2005, and National Tariff Policy 2006. According to the report [28]

Table 2
Synopsis of India's twelfth five year plan (1 April, 2012–31 March, 2017).

Twelfth five-year plan (1 April, 2012–31 March, 2017)	
Total installed capacity at start of plan period	199,877 MW
Estimated demand over plan period	276,000 MW
Planned expansion in plan period	75,785 MW
Increase in expansion of power generation by type	
Thermal (inc. coal & lignite)	59,870 MW
Hydro	10,897 MW
Nuclear	5300 MW
Imported energy	1200 MW
Renewables total planned expansion 30,000 MW	
Wind	15,000 MW
Solar	10,000 MW
Small Hydro	2100 MW
Bio-mass	2900 MW

Table 3
Plan wise capacity addition in grid interactive renewable power in India (As on 31st Jan. 2012).

Resource	Estimated potential (MW)	Up to 9th plan – achievement	10th plan – achievement	11th plan achievement up to 31.01.2012	Cumulative Achievements up to 31.01.2012
Wind power	48,500	1667	5427	9085.00	16179.00
Small hydro power	15,000	1438	538	1324.13	3300.13
Biomass power*	23,700	390	795	1910.13	3095.13
Solar power	20–30 MW/km^2	2	1	478.48	481.48
Waste to energy	–	–	–		73.66
Total		**3475**	**6761**	**12893.40**	**23129.40**

* Including biomass power, bagasse cogeneration, urban and industrial waste to energy (Akshya Urja magazine) [27].

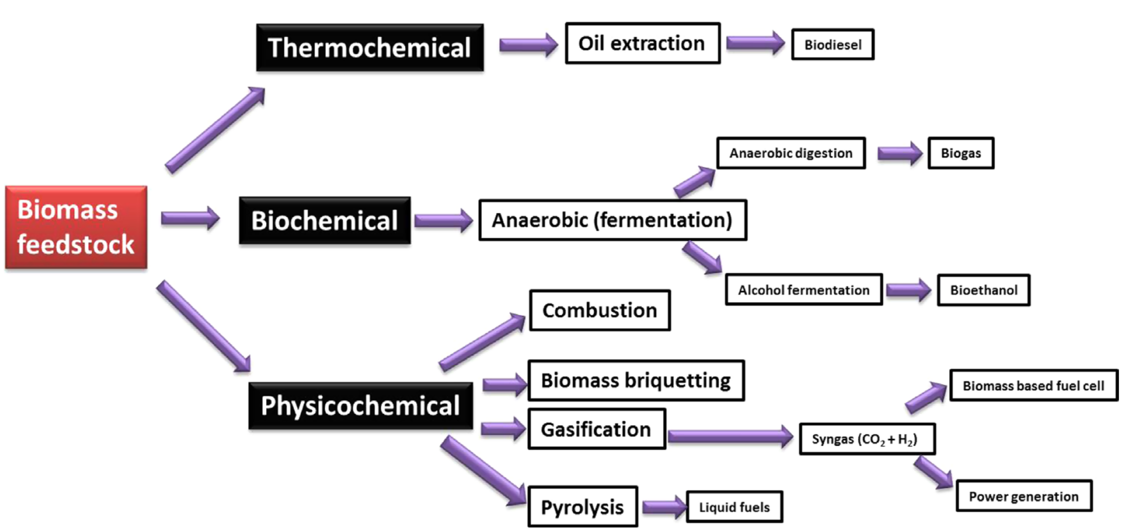


Fig. 5. Main conversion processes from biomass to energy.

Table 4
Technologies involved in production of various biofuels from different sources.

Feed-stocks	Technologies	Biofuels
Sugar, starch crops, and lignocellulosic biomass	Fermentation	Bioethanol
Oil crops and lignocellulosic biomass	Transesterification	Biodiesel
Sugar, starch crops, and lignocellulosic biomass	Saccharification/ fermentation	Biobutanol
Agriculture and animal wastes and lignocellulosic biomass	Anaerobic fermentation	Biogas
Lignocellulosic biomass	Microbial photolysis/ fermentation	Biohydrogen

the estimates for the twelfth five year plan (2012–2017) including the carry-over from the eleventh plan is presented in Table 2.

Among all renewable energy sources, traditional biomass, such as wood and cow dung, has played a key role in India's energy supply particularly in rural sector. India can make use of organic and agricultural waste for its bioenergy production. About 4 million household biogas plants along with 4000 additional units supplying household clusters or villages have been installed in India. MNRE has estimated that available cattle manure may support approximately 12 million household biogas plants. 48 Big biogas plants using industrial wastewater have already been installed in India to generate 70 MW electricity [29]. Government of India may shortly announce a biomass power policy to generate 10,000 MW electricity by 2020. Plan wise capacity addition of grid interactive renewable power in India is given in Table 3.

4. Technologies for conversion of biomass to energy

Increase in oil prices, energy security fears, and the domestic reform of agricultural policies compel for a serious consideration of biofuel in developing countries. Biomass can be used directly as fuel but will generate environmental pollution [30]. A variety of biomass feedstocks are available for exploitation and conversion into biofuels as well as for power generation [31]. There are five different ways to obtain energy from biomass: (i) crops from which starch, sugar, cellulose, and oil can be obtained, (ii) burning solid waste, (iii) biogas used to generate heat/electricity by anaerobic digesters, (iv) landfill production for methane and (v) biofuel production such as ethanol, methanol, biodiesel and their derivatives.

Biomass to bioenergy conversion routes consist of a series of conversion steps by which a raw biomass feedstock is transformed into a final energy product (heat, electricity, or transport biofuel). Three main classes of conversion routes can be identified and discussed (Fig. 5):

1. Çombustible fraction of the waste is converted into high-energy fuel pellets which may be used in steam generation. The waste is first dried to bring down the high moisture levels. Sand, grit, and other incombustible matter are then mechanically separated before the waste is compacted and converted into pellets. Fuel pellets have several distinct advantages over coal and wood because they are cleaner, free from incombustibles, have lower ash and moisture contents, are of uniform size, cost-effective, and eco-friendly.
2. Biochemical routes: Biochemical processes, like anaerobic digestion, can also produce clean energy in the form of biogas which can be converted to power and heat using a gas engine. Anaerobic digestion is the natural biological process which stabilizes organic waste in the absence of air and transforms it into biofertilizer and biogas. Anaerobic digestion is a reliable technology for the treatment of wet, organic waste. Organic waste from various sources is biochemically degraded in highly controlled, oxygen-free conditions circumstances resulting in the production of biogas, which can be used to produce both electricity and heat.
   In addition, a variety of fuels can be produced from waste resources including liquid fuels, such as ethanol, methanol, biodiesel, Fischer–Tropsch diesel, and gaseous fuels, such as hydrogen and methane. The resource base for biofuel production is composed of a wide variety of forestry and agricultural resources, industrial processing residues, and municipal solid and urban wood residues. Globally, biofuels are most commonly used to power vehicles, heat homes, and for cooking.

4.1. Biomass for power and heat

4.1.1. Combustion

Biomass on combustion gives heat, which is used in generating electricity. High-pressure steam is generated by burning the biogas in a boiler. The steam so obtained is allowed to flow in a series of turbine blades, where turbine rotates. The turbine is connected to an electric generator that rotates and produces electricity. This is a widely available, commercial technology.

4.1.2. Combined heat and power

Most biomass-fired steam turbine plants are located at industrial sites. Waste heat at factory sites obtained from the steam turbine can be recovered and used. Combination of heat and power (CHP) facilities (also called cogeneration facilities) are highly resource efficient and provide increased levels of energy services per unit of biomass consumed compared to facilities that generate power only.

4.2. Biogas

4.2.1. Gasification

Since biomass is a solid, it can be a cumbersome fuel source like coal. If biomass is converted into a gas, it can be made available for different energy devices. Gases obtained from biomass can be burned directly for heating or generating electricity [32]. Gasifiers operate by heating biomass in an environment where the solid biomass breaks down to form a flammable gas. The biogas can be purified to remove undesirable chemicals. From gasification of biomass, methanol, hydrogen, and Fischer–Tropsch diesel can be produced.

4.2.2. Anaerobic digestion

Anaerobic digestion is a type of fermentation that converts organic material into biogas. The biogas thus produced consists of mainly methane (60%) and carbon dioxide (40%).

4.3. Biofuels

As discussed above, it is essential to convert biomass into liquid fuels, which can reduce our dependence on import of petroleum and diesel fuels and power our economy. Biofuel consists of solid, liquid, or gaseous fuels. Biofuels can be categorized into first, second, third and fourth generation biofuels according to source, type, and technological process of conversion. There are several established technological processes utilized in the production of various biofuels from different sources (Table 4).

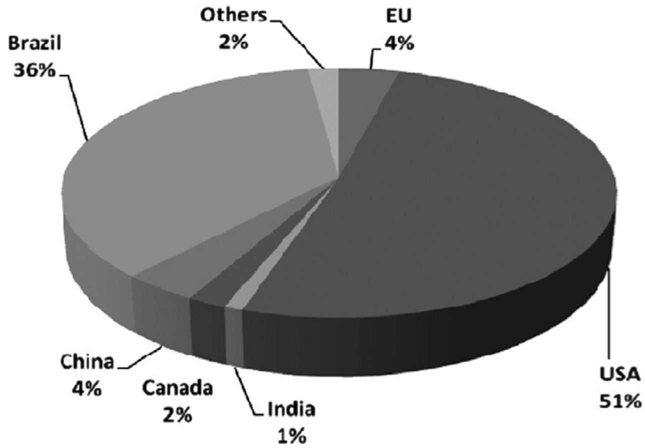


Fig. 6. Ethanol production by country: 2010 [22].

4.3.1. Classification of biofuels [33]

As per European classification, the biofuels have been divided into the following categories.

Liquid biofuels:

- Bioethanol obtained from biomass can be used as biofuel E5 (5% ethanol and 95% petrol) or as biofuel E85 (85% ethanol and 15% petrol).
- Biodiesel containing methyl-esters [pure vegetable oils (PME), rapeseed methyl esters (RME) and fatty acid methyl esters (FAME)] are produced from vegetable oil, animal oil or recycled fats and oils.
- Biomethanol produced from biomass can be used as biofuel.
- Bioethyl-tertio-butyl-ether (ETBE) produced from bioethanol can be used as a petrol additive (47%) to increase the octane rating and to reduce knocking.
- Biomethyl-tertio-butyl-ether (MTBE) produced from biomethanol is used for the same purposes as BioETBE and added to petrol (36%).
- BtL, liquid fractions, or mixtures produced from biomass are used as biofuels or fuel ingredients.
- Pure vegetable oils (PVO) produced by pressing, extraction or other methods after refining can be used as biofuel if compatible with the engine involved.

Gaseous biofuels:

- BioDME transport fuels can be used directly as biofuel for compression–ignition engines.
- Biohydrogen as biofuel produced from biomass or the biodegradable fractions of waste.

Other renewable fuels, that is Biofuels not named above:

Biofuels have been divided into first generation biofuels (conventional biofuels) and second-generation biofuels (advanced biofuels).

The first generation biofuels include (i) Bioethanol (BioEtOH or BioEt), conventionally known as ethanol and obtained through hydrolysis and fermentation of raw materials such as cereals, sugar beets, (ii) Pure vegetable oils obtained through cold pressing and extraction from seeds of oil plants, (iii) Biodiesel, consisting of RME or FAME and fatty acid ethyl esters (FAEE) of higher fatty acids of other oily plants and obtained as a result of cold pressing, extraction and transesterification, (iv) Biodiesel, consisting of methyl and ethyl esters and obtained as a result of transesterification of post-frying oil, (v) Biogas produced from purification of wet landfill and (vi) BioETBE obtained by chemical processing of bioethanol.

The second-generation biofuel feedstock comprises of biomass, waste vegetable oils and animal fats, as well as waste of organic origin that are useless in the food and forestry industries. The second generation of biofuels includes bioethanol, biobutanol, and blends of higher alcohols and derivative compounds from hydrolysis and fermentation of lignocellulosic biomass.

The third generation biofuels may be obtained in a similar way as in the case of second-generation biofuels. However, in this case the feedstock (biomass) is modified at the plant growing stage with the use of molecular biology techniques. In order to reduce CO_2 and its impact, fourth generation biofuel technologies should be developed considering the Carbon Capture and Storage (CCS) at the raw material preparation and biofuel production stages.

4.3.2. Production processes for biofuels

Biofuel production processes are discussed below.

4.3.2.1. Bioethanol production. In recent years, bioethanol has received considerable interests at national and international levels. The global market for bioethanol has entered a phase of rapid, transitional growth [34] and ethanol fuel production reached 86 billion l (23 billion gal US) in 2010. United States and Brazil together produce 87.5% of the global production [11]. The world bioethanol production is expected to reach 100 billion l in 2015 [34]. It is expected that 442 billion l of bioethanol can be obtained from lignocellulosic biomass and 491 billion l of bioethanol per year can be obtained from crop residues and crop wastes [35]. Fig. 6 shows global bioethanol production in 2010.

Energy crops such as sugarcane, maize, beets, yam, or sweet sorghum are primarily responsible for ethanol, butanol, and methanol production [36]. Bioethanol represents one of the most promising biofuels, exhibiting several advantages, such as high octane number, low cetane number high heat of vaporization and, most importantly, reduction of greenhouse gas emissions.

A variety of biomass feedstocks have been explored for ethanol production including sucrose rich crops such as sugarcane and sugar beet, starch-rich crops such as maize and grain sorghum and lignocellulosic materials such as woody biomass, herbaceous perennials, and various wastes [37]. Lignocellulosic biomass is the most abundant renewable resources on the Earth. The use of lignocellulosic materials for second-generation ethanol production is considered to minimize the conflict between land use for food, feed and energy production.

The production of biofuels from ligno-cellulosic feedstocks can be achieved through two very different processing routes [38]:

(i) Biochemical process: In this process enzymes and other micro-organisms are used to convert cellulose and hemicellulose components of the feedstock's to sugars prior to their fermentation to produce ethanol.
(ii) Thermo-chemical process: Using pyrolysis/gasification technologies syngas is produced. Using Fischer–Tropsch conversion process many long carbon chain biofuels, such as synthetic diesel, aviation fuel, or ethanol produced from syngas can be reformed.

For the biochemical process, many things are to be done in terms of improving feedstock characteristics, reducing the costs by perfecting the pre-treatment process and improving overall process [39–41].

A major problem in the processing of lignocellulosic materials is the natural resistance of these materials to the conversion process required to generate fermentable sugars due to the presence of lignin and the degree of crystallinity of cellulose. A suitable pretreatment of biomass is essential to the success of subsequent steps of saccharification and fermentation; the goal is

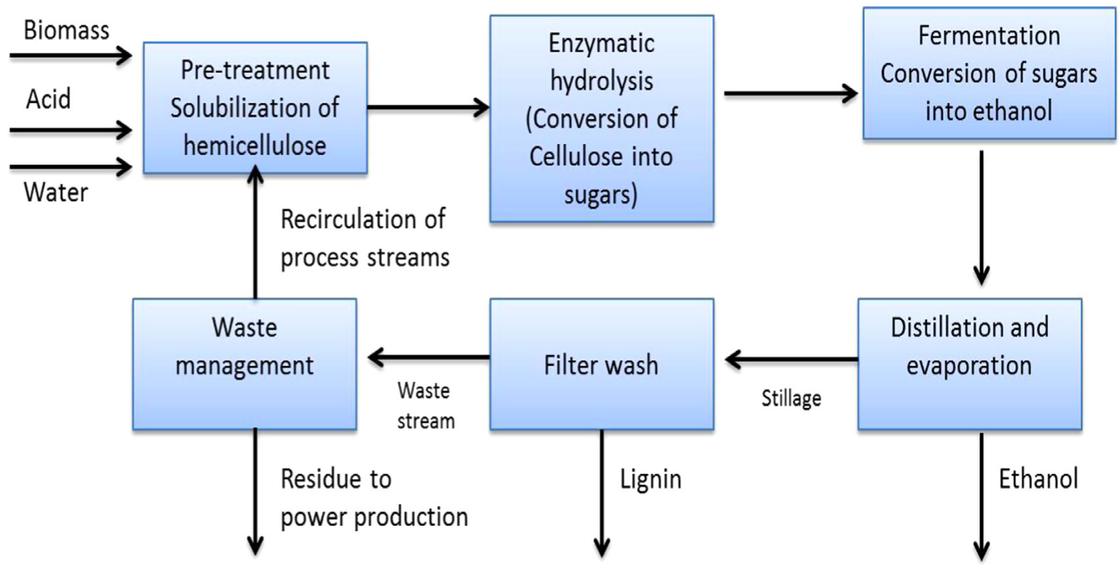


Fig. 7. An overview of the production of ethanol from cellulosic biomass.

Table 5
Comparison of sugarcane, tropical sugar beet and sweet sorghum.

	Sugarcane	Tropical sugar beet	Sweet sorghum
Crop duration	About 12–13 months	About 5–6 months	About 3½ months
Growing season	Only one season	Throughout the year (10 months), except rainy period	All season- kharif, Rabi and summer
Soil requirement	Grow well in loamy soil	Grow well in sandy loam. Also tolerate alkalinity	All types of drained soil
Water management	Require water throughout the year	Less water requirement. 40–60 percent compared to sugarcane.	Less water requirement. Can be grown as rain fed crop
Crop management	*Require good management. Low fertilizer required. Less pest and disease complex*	More fertilizer requirement. Require moderate management.	*Low fertilizer requirement and less pest and disease complex. Easy management*
Yield per acre	25–30 ton	30–40 ton	20–25 ton
Sugar content on weight	8–12 percent	15–18 percent	8–10 percent
Sugar yield	2.5–4.8 ton/acre	4.5–7.2 ton/acre	2–3 ton/acre
Ethanol production directly from juice		2800–4100 litre/acre	1140–1640 litre/acre
Harvesting	Difficult and laborious	Very simple, both manual and with simple small mechanical machine can be used	Very simple, both manual and with simple small mechanical machine can be used

to break the lignin seal and disrupt the crystalline structure of cellulose [40]. Pretreatment is responsible to separate the components of the lignocellulosic biomass, reducing the crystallinity of the material, making the cellulose accessible, and removing the lignin [42].

The main types of pretreatment include the thermo-chemical methods, such as steam explosion, followed by chemical methods with alkalis or acids, and the biological method, with enzymes or whole cells. Physical treatments such as drying, grinding, and granulometric classification are initial steps common to most processes that involve the use of lignocellulosic biomass. Thermo-chemical methods cause the disruption of the material's structure, degradation of hemicellulose and cellulose and lignin transformation, thus facilitating the subsequent hydrolysis of cellulose. Steam explosion, alkali washing, and dilute acid hydrolysis are some thermo-chemical methods for pre-treating and hydrolyzing lignocellulosic materials. Microbial treatment is also capable of lignin removal, but it requires longer retention times than thermo-chemical methods.

The complexity of the production process depends on the type of feedstock used in the process [43]. Amongst the new advances in this field, process integration is the key factor for reducing the cost in ethanol production and increasing bioethanol competitiveness related to gasoline. However, biomass pretreatment remains a bottleneck in the bioprocessing of lignocellulosics for biofuels and other bioproducts [44]. Fig. 7 shows the basic steps in the production of ethanol from cellulosic biomass. There are a variety of options for pretreatment and other steps in the process [45].

Molasses obtained from the sugar industry is the main feedstock for ethanol production in India. In 2007, India produced 200 million l of ethanol and was the world's seventh largest ethanol producer. Sweet Sorghum, a grass type plant similar to sugarcane, is another potential alternative substrate to meet the growing demand of bioethanol. Both sweet sorghum and tropical sugar beet offer advantages over sugarcane as given in Table 5.

Microalgae are feasible as a biofuel feedstock by taking the cultivation technique into consideration [46]. Fig. 8 gives an overall summary of ethanol production from microalgae.

4.3.2.2. Biodiesel production. Biodiesel refers to a biomass-based diesel fuel consisting of long-chain alkyl (methyl, propyl or ethyl) esters and can be used for transport vehicles. Biodiesel has the following distinct advantages over petro diesel [47]:

1. It is derived from renewable domestic resources and reduces the dependence on petroleum.
2. It is biodegradable and ecofriendly.
3. It has higher flash point, safer for handling and storage.
4. It has an excellent lubricity.

Ministry of Petroleum and Natural Gas announced a Bio-diesel Purchase Policy in October 2005 to encourage production of biodiesel in the country. Biodiesel research, production, and marketing in India are in the early stages of development.

Biodiesel is obtained from the vegetable oils and animal fats through the esterification and transesterification reactions [48]. Biodiesel is miscible with petrodiesel in all ratios [47]. Depending on the quality of feedstock's, production process of biodiesel can be changed.

Feedstock's for biodiesel production

There are several feedstock's for biodiesel production such as non-edible oils waste cooking oils, animal fat waste, lipids from oleaginous fungi, oil production from microbial cell cultivations, and algal biomass. In many parts of the world, biodiesel is produced from more than 95% feedstock's obtained from edible oils. The type and choice of feedstock for biodiesel production is country specific and depends on availability of feedstock. Non-edible oil is the most suitable feedstock for biodiesel as they cannot be utilized for food purposes and also by increase demand for edible oil in the current situation. In India and Southeast Asia, the jatropha tree (*Jatropha curcas*), karanja (*Pongamia pinnata*), and mahua (*M. indica*) are used as significant fuel sources [11]. Use of non-edible oil seed plants are reviewed by Kumar and Sharma [13] and Borugadda and Goud [48]. List of biofuel seeds used for biodiesel production in India are given in Table 6.

Biodiesel production

Global biodiesel production in 2010 is given in Fig. 9. In the production process, oil, alcohol, and catalyst are mixed in a reactor and stirred for 1 h at 60 °C. Smaller plants often use batch reactors [49], but larger plants (> 4 million l/year) use continuous flow processes involving continuous stirred tank reactors (CSTR) or plug flow reactors [50]. Attempts are being made to simplify the existing biodiesel production technologies by using co-solvents, supercritical solvents, new catalysts (including heterogeneous and biocatalysts) and the efforts are made in search of new blends and raw materials (including the waste glycerol) to increase the amount of biofuel produced on a given agricultural area [51–57].

Transesterification is a universal and established method for biodiesel production around the world. In general, transesterification is done in two different ways. In the first method, a catalyst is used whereas in the second method a non-catalyst option such as supercritical processes and co-solvent systems are used. Various catalysts used are base catalysts that include

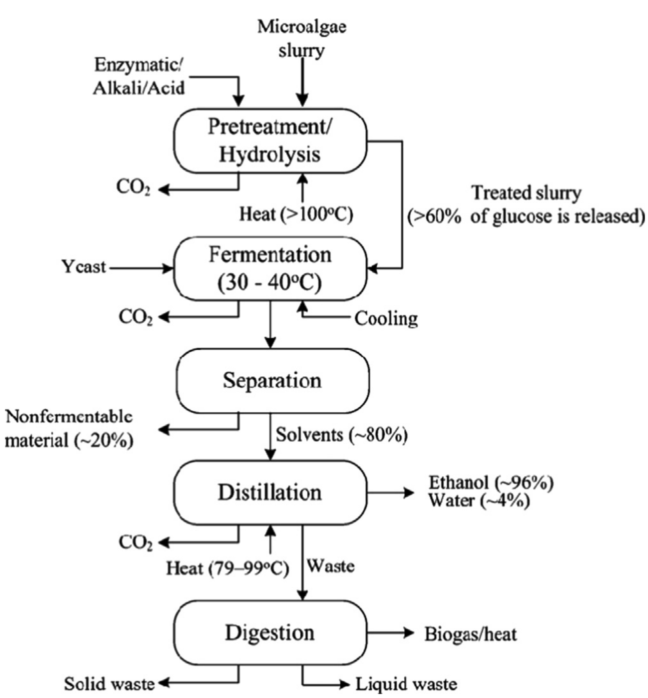


Fig. 8. An overall summary of ethanol production from microalgae [85].

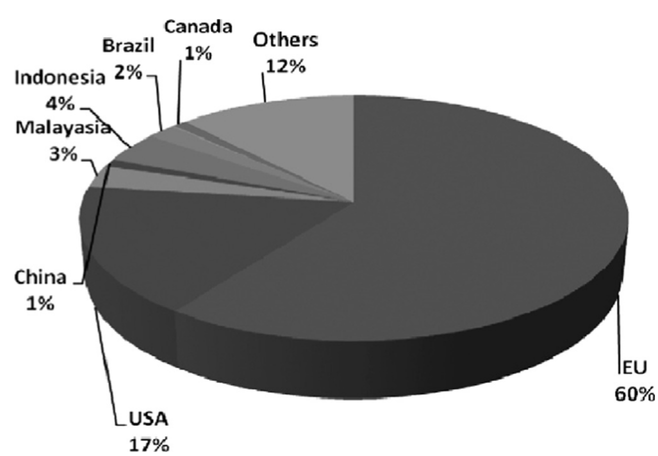
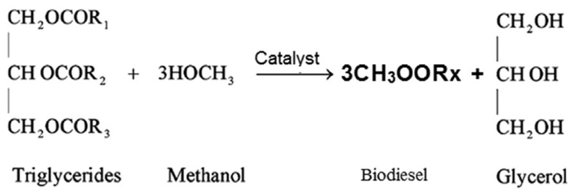


Fig. 9. Biodiesel production by country wise: 2010 [22].

Table 6
Selected non-edible oil seed plants in India.

Botanical name	Distribution	Oil (%)	References
Jatropha curcas (Jatropha)	All over India	40–60	Kumar and Sharma [1]; No [74]
Pongamia pinnata (Karanja)	Maharashtra, Karnataka, Assam	30–40	Karmee and Chadha [75]
Garcinia indica (Kokum)	Western Ghats region, Andaman and Nicobar Islands, North-eastern region of India	–	Jain and Sharma [76]
Madhuca indica	All over India	50%	Jena et al. [77]
Euphorbia lathyris L.	South West Asia	48%	Wang et al. [78]
Cerbera odollam (Sea mango)	Coastal salt swamps and creeks in south India	54%	Kansedo et al. [79]
Moringa oleifera (Moringa)	Himalayan regions of northwest India	33–41	Da Silva et al. [80]
Azadirachta indica (Neem)	All over India	35–45	Jain and Sharma [76]
Guizotia abyssinica	India	30%	Sarin et al. [81]
Argemone mexicana L.	All over India	22–36%	Kumar and Sharma [2]
Sapindus mukorossi (Soapnut)	Andhra Pradesh, Karnataka, Maharashtra, Delhi, Tamil Nadu	23%	Misra and Murthy [82]
Ricinus communis (Castor)	All over India	46–55	Ogunniyi [83]

NaOH, KOH, and NaMeO; acid catalysts that include H_2SO_4, H_3PO_4, and $CaCO_3$ and lipase enzymes [48]. Methanol and ethanol are the two main light alcohols used for the transesterification process. Transesterification is a multistep process but the overall reaction is given below [58].



Transesterification process

R_1, R_2 and R_3 are fatty acid alkyl groups (could be different or the same) and depend on the type of oil. The fatty acids involved determine the final properties of the biodiesel (cetane number, cold flow properties, etc.)

For transesterification reaction both homogeneous (alkalies and acids) and heterogeneous catalysts are used. In order to overcome the shortcomings of the homogeneous catalysts, heterogeneous catalysts have been used [48]. During transesterification process the triglyceride (TG) is converted stepwise into diglycerides (DG), monoglycerides (MG) and finally glycerol (GLY) and a mole of FAME is liberated at each step.

Neem oil can also be used as fuel in diesel engines directly and also by blending with methanol. Neem oil with a high calorific value matches diesel. Its blends with diesel substituting nearly 35% of the later have been suggested for use without any major engine modification and without any worthwhile drop in engine efficiency [59].

4.3.2.3. Thermochemical biofuels. Bio-methanation, fermentation, and thermochemical pathways have been used for the conversion of biomass to biofuels as energy sources [60]. There are a number of technologies to convert biomass resources into power, heat, and fuels. Depending on the type and characteristics of biomass, biological, physical, chemical, or combinations of processes are used for the manufacture of biofuels. Biogas, ethanol, and biodiesel can be produced via microbial/enzymatic fermentations [61–62], whereas conversion of biomass into bio-oil, biochar, syngas, and others requires entirely thermo-chemical processes [38].

4.3.2.3.1. Bio-oil. Bio-oil is a kind of liquid fuel made from biomass materials and is a complex mixture of chemical compounds that are obtained from the decomposition of cellulose, hemicelluloses, and lignin along with other organic entities [63]. In bio-oils, there are a number of organic compounds belonging to sugars, organic acids, alcohols, aldehydes, ketones, phenols, esters, ethers, furans, nitrogen and sulfur compounds, and multifunctional compounds [64]. Biomass can be converted to bio-oil by fast pyrolysis, liquefaction and gasification processes. The stability of bio-oils is of great concern as once pyrolysis is over, bio-oils start degrading or undergoes further reactions [65].

4.3.2.4. Non-condensable pyrolysis gas. Pyrolysis is a thermochemical decomposition of organic material at elevated temperatures in the absence of oxygen and is composed of various gases such as CO_2, CO, NO_x, SO_x, H_2S, H_2, aldehydes, ketones, volatile carboxylic acids, and gaseous hydrocarbons. The presence of potential pollutant gases NO_x, SO_x, H_2S, and aerosols in pyrolysis gases depends upon the biomass source. However, there are many options for the purification of the pyrolysis gases [66].

4.3.2.5. Bio-methane. Bio-methane can be produced from a wide range of conventional lignocellulosic biomass and like ethanol, bio-methane has the potential to produce more energy than any other type of bio-fuel (e.g. bio-diesel, bio-ethanol) [67]. Other lignocellulosic materials obtained from sunflowers and alpine grass have also been reported as potential substrate for methane production (2600–4,550 metric ton/ha/year) [68].

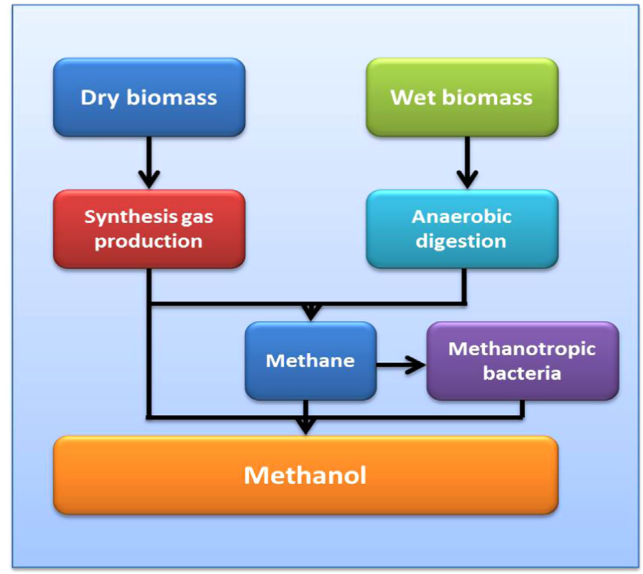


Fig. 10. Process for manufacture of methanol from biomass.

4.3.2.6. Biomethanol. Methanol is one of the important bulk platform chemicals produced by the chemical industry. Methanol is also known as methyl alcohol, wood alcohol, or wood spirits, and is often abbreviated as MeOH. It is used to make various other chemicals.

Bio-methanol is chemically identical to conventional methanol and miscible with water, petrol and many organic compounds. It burns with an almost invisible flame. Its toxicity (mortality) is comparable to or better than gasoline. It also biodegrades quickly (compared to petroleum fuels) if spilled. Biomass can be converted to MeOH via thermochemical and biotechnological pathways (Fig. 10).

An interesting concept of using biomass to produce methanol is the co-processing of biomass and fossil resources, e.g. co-gasification of biomass with coal or natural gas. In the production of biodiesel, methanol is required and glycerol is produced as a byproduct. The glycerol can be converted into methanol. The scope of the supermethanol concept is schematically outlined in Fig. 11.

4.3.2.6.1. Thermochemical pathways for biomethanol. The thermochemical conversion paths to MeOH are basically the same as for fossil feedstock's, such as coal or natural gas. The biomass is gasified and the resulting synthesized gas, a mixture of CO, H_2 and CO_2, is adapted to the quality requirements of MeOH synthesis. During synthesis the following reactions occur:

$$CO + 2H_2 \rightarrow CH_3OH$$

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

$$CO_2 + H_2 \rightarrow CO + H_2O$$

The formation of MeOH is exothermic and is favored by high pressures and low temperatures. For reasons of process simplification, investment cost reduction and energy consumption reduction; alternatives are under development, which could also be used for MeOH production from biomass. Direct oxidation of methane gives methanol.

$$2CH_4 + O_2 \rightarrow 2CH_3OH$$

4.3.2.6.2. Biochemical pathways for biomethanol. One biochemical route is via methane formation by anaerobic digestion. This process is well developed due to the rise of biogas production from municipal waste or landfill sites. The biogas has to be cleaned to obtain a gas with high methane content and MeOH is then produced from the methane as described above. Recently a biochemical route using methanothrophic bacteria has been investigated. For example, bacteria such as *Methylococcus capsulatus* will convert methane to MeOH if methane is the only available resource. The production costs of bio-methanol are affected by local conditions. Bio-methanol can be co-produced along with hydrogen, bio-ethanol, and urea.

4.3.2.7. Hydrogen production from biomass. Hydrogen is the highest in energy content per unit mass among known fuels (120.7 kJ/g) but the energy content per unit volume is low. Storage of hydrogen for civilian applications poses more problems as compared to storage of liquid fossil fuels. When hydrogen is burnt, it produces water as a by-product and is therefore not only an efficient energy carrier but a clean, environmentally benign fuel as well. Hydrogen can be used for power generation and also for transport applications. Hydrogen energy is often considered as a potential solution for several challenges that the global energy system is facing.

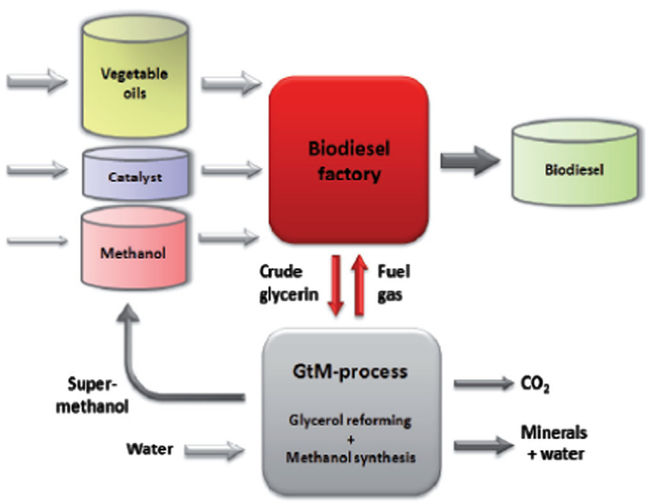


Fig. 11. Outline of the supermethanol concept. The glycerol-to-methanol (GtM-) process is the process under investigation in the supermethanol project [86].

The advantages are the fact that hydrogen use results in nearly zero emissions at end-use. Production of hydrogen from biomass has been tipped as one of the more suitable energy carriers from the technological and environmental perspective, particularly within the context of sustainable development. Hydrogen can also be produced using locally available resources including natural gas, coal and nuclear, biomass and other renewables including solar, wind, hydroelectric or geothermal energy. Hydrogen has desirable characteristics and its energy content (120.7 kJ/g that is the highest energy content per unit mass among known fuels) makes it the fuel of the future. It is recyclable, non-polluting, yields only water after combustion, and has high conversion efficiency. Different processes for manufacture of biohydrogen from different feedstocks are given in Table 7 [69]. Advantages and disadvantages are also given in the same table. There are various routes for producing hydrogen from biomass using thermal and biochemical methods (Fig. 12). Among various hydrogen production processes, biohydrogen production technology has the unique possibility of using renewable energy sources like biomass. Biohydrogen technologies provide a wide range of approaches including direct and indirect photolysis, photo-fermentation, and dark fermentation. Tables 7 and 8 summarizes various biological production processes [70].

The processes are known to be less energy intensive because they can be carried out at ambient temperature and pressure. Biological methods mainly include photosynthetic and fermentative hydrogen production and are associated with the activity of two very common enzymes (hydrogenase and nitrogenase) [71] (Table 9). A number of studies have been carried out all over the world to produce biohydrogen from various sources including industrial wastewaters. Various research, development, and demonstration activities on different aspects of hydrogen energy that includes hydrogen production, its storage and applications for motive power and power generation through internal combustion engine and fuel cell based systems, have been pursued by academic institutions, Council for Scientific and Industrial Research (CSIR) laboratories, industry, etc. with the support of Government of India, for more than two decades. As a result, laboratory scale prototypes have been developed and some of them include (a) bio-hydrogen production using distillery wastes; (b) Proton Exchange Membrane (PEM) based electrolyzers for hydrogen production through splitting of water and water–methanol mixture; (c) inter-metallic hydride with storage capacity up to 2.42 wt%; (d) liquid organic hydrides for hydrogen storage with

Table 7
Comparison of biohydrogen production technologies.

Process	Feedstock's	Advantages	Disadvantages
Biomass gasification	Lignocellulosic Biomass	35–50 percent efficiency gives carbonaceous material with oil, chemicals and minerals	Catalyst deactivation occurs CO, CO_2, CH_4 as by products
BioH_2: photolysis	H_2O + sunlight	0.5 percent efficiency H2 can be produced directly from water and sunlight	Requires high intensity of light, low photochemical efficiency, O_2 is inhibitory in direct photolysis.
BioH_2: photofermentation	Organic acids + sunlight	0.1 percent efficiency A wide spectral energy can be used by photosynthetic bacteria	CO_2 is a byproduct.
BioH_2: dark fermentation	Biomass including lignocellulosics and lignocelluloses hydrolysis products viz. five and/or six carbon sugars.	Produce H_2 under anaerobic conditions without light. 60–80 percent efficiency (maximum theoretical yield of 4 moles hydrogen per mole glucose catabolized). Produce hydrogen under anaerobic conditions without light. No oxygen limitations can produce several metabolites as by-products. Various substrates can be used.	Relatively lower hydrogen yield. At higher hydrogen yield, process becomes thermodynamically unfavorable. CO2 is a byproduct.

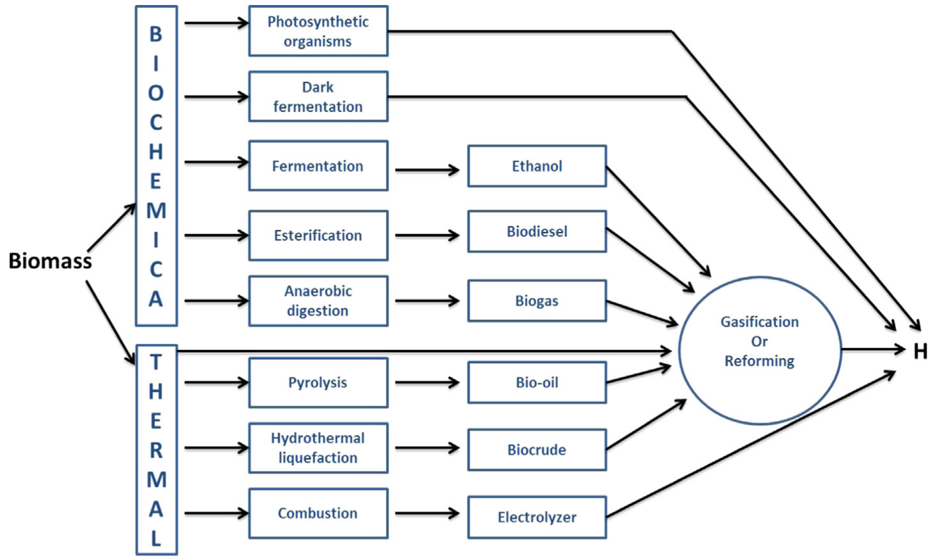


Fig. 12. Routes of hydrogen production from biomass.

Table 8
Different biological hydrogen production processes with their advantages.

Process	General reactions and broad classification of microorganisms used	Advantages
Direct biophotolysis	$2H_2O+light=2H_2+O_2$ Microalgae	(i) Can produce H_2 directly from water and sunlight (ii) Solar conversion energy increased by 10-folds as compared to tree crops
Indirect biophotolysis	$6H_2O+6CO_2+Light=C_6H_{12}O_6$ $C_6H_{12}O_6+2H_2O=4H_2+2CH_3COOH+2CO_2$ $2CH_3COOH+4H_2O+light=8H_2+4CO_2$ Overall reaction $12H_2O+light=12H_2+6O_2$	(i) Can produce H_2 from water (ii) Has the ability to fix N_2 from atmosphere
Dark fermentation	$C_6H_{12}O_6+6H_2O=12H_2+6CO_2$ Fermentative bacteria	(i) It can produce H_2 all day long without light (ii) A variety of carbon sources can be used as substrates (iii) It produces valuable metabolites such as butyric, lactic acid as by products (iv) It is anaerobic process, so there is no O_2 limitation problem
Photo-fermentation	$2CH_3COOH+2H_2O+light=4H_2+2CO_2$ Purple bacteria Microalgae	(i) A wide spectral light energy problem can be used by these bacteria (ii) Can use different waste material
Hybrid reactor system (combined dark and photo-fermentation)	Stage 1 $C_6H_{12}O_6+2H_2O=4H_2+2CH_3COOH+2CO_2$ Stage 2 $2CH_3COOH+2H_2O+light=4H_2+2CO_2$ Fermentative bacteria followed by anoxygenic phototrophic bacteria (PNS)	Two stage fermentation can improve the overall yield of hydrogen

Table 9
Mode of hydrogen production from group of bacteria.

Mode	Aerobic/anaerobic process	Groups of bacteria
Fermentative	Strict anaerobes Facultative anaerobes	*Clostridium* Sp., *Caldicellulosiruptors accharolyticus* *Enetrobacter aerogenes, Escherichia coli, Citrobacter* Sp
Photosynthetic	Oxygenic Anoxygenic	Cyanobacteria- *Anabaena variabilis*, *Nostoc punctiforme*, Green algae – *Chlamydomonas reinhardtii* *Rhodobacter sphaeroides, Rhodospirillum rubrum*

storage capacity of about 6 wt%; (e) methanol reformer for production of hydrogen, which can be used in PEM fuel cells; (f) hydrogen catalytic combustion cookers; (g) hydrogen fueled motor-cycles and three wheelers with hydrogen storage in metal hydrides; (h) hydrogen fueled three wheelers with hydrogen storage in high pressure composite cylinders; (i) hydrogen fueled internal

combustion engine for stationary power generation; (j) phosphoric acid fuel cells with stacks up to 25 kW capacity; (k) PEM fuel cells with stacks up to 5 kW capacity; (l) the UPS system based on PEM fuel cell; (m) fuel cell battery hybrid van; (n) hydrogen blended CNG (H-CNG) fueled vehicles, etc. [72]. Use and applications of hydrogen are in the early demonstration stages in the country both for transport and for stationary power generation.

Development of cost effective biohydrogen production is still in its nascent stage and a number of issues still have to be addressed. Among these, utilization of organic load, use of starch rich solid wastes, industrial wastewaters with pre-treatment, forms an attractive approach for biohydrogen production in the future. The development of a sequential or combined hybrid bioprocess for hydrogen and methane production would prove to be viable in the long run. However, some major aspects need indispensable optimization including identification of a suitable substrate, suitable pre-treatment method/s, development of ideal microbial culture/consortia that can convert the substrate efficiently to hydrogen and methane, suitable hybrid bioreactors to achieve the desired results, etc.

5. Latest development in biomass technologies

- HIMURJA has set up an energy park in Himachal Pradesh. This energy park provides a forum to general public where they can understand different renewable energy applications by operating working models of renewable energy devices.
- In Haryana, biomass project of 9.9 MW has been set up in Mahendragarh district with a total cost of Rs. 60 crore and a similar project of 9.5 MW in Bhiwani district is at its final stage of completion.
- 70% of the country's population have only limited access to electricity. Presently, India has a total installed capacity of 3000 MW of biomass-based power generation. The ministry of new and renewable energy is targeting to double this capacity during the 12th Plan (2012–17).The ministry has earmarked 3400 crore for the various incentive schemes under this mission.
- In terms of the total financial support provided by the MNRE during the 11th Plan Period, hydrogen energy and fuel cell projects were provided with a budget of about Rs. 118 crore out of the total R&D support of about Rs. 507 crore.
- Cumulative deployment of various renewable energy in the country as on 31st October 2013 are (i) Grid interactive power (capacities in MW) (a). biomass power 1284.80, (b). bagasse cogeneration 2392.48 (ii) off-grid interactive power (capacities in MWEQ) (a). biomass (non-bagasse) cogeneration 493.69, (b). biomass gasifiers 16.924 (rural), 146.32 (industrial) (c). biogas based energy system-nil. (iii) Family biogas plants 46.83 lakhs.

6. Future of biomass energy in India

Biomass, as a clean and cost-effective fuel option has tremendous potential for applications in India. Necessary expertise and infrastructural facilities about most of the biomass energy technologies already exist. There is just a need to allocate necessary resources for improving these technologies and development of plan for widespread dissemination. As part of the National Action Plan on Climate Change (NAPCC), the Government of India has proposed a National Bio-energy Mission during the 12th plan (2012–2017). Future of biomass energy depends on providing reliable energy services at competitive cost. In India, this will happen only if biomass energy services can compete on a fair market. A well-structured, centralized, coherent, and consistent biofuel policy at the national and state level is the immediate need of the hour. There is a need to provide incentives for bioenergy programs. Public and private partnerships need to be encouraged in the development of biomass energy technologies. India also needs a long-term vision to enable bioenergy journey to reach its desired destination.

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